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UCID-21719

Summary Report on the October 1989 SDIO Laser,
Propulsion Workshop

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June 1989

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Summary Report on the October 1988 SDIO Laser Propulsion Workshop

October 17-18, 1988
Stanford University
Stanford, CA

The Fall 1988 Workshop of the SDIO Laser Propulsion Program was held at Stanford University on October 17-18, 1988. The Workshop concentrated on the double-pulse planar thruster which has been the focus of the Program. Theoretical and computer modelling results were presented by Physical Sciences, Inc. (PSI) and by the Stanford University group. Several groups presented new results from small scale experiments. The double-pulse concept illustrated in figure 1 has been shown to work, in that two closely spaced pulses do remove less mass and produce thrust with higher efficiency than a single pulse (or two widely spaced pulses) with the same total energy. However, the best efficiencies reported are still only about 10% (kinetic energy of exhaust/total laser energy in), although specific impulses of 600 to 1000 seconds appear to be easy to achieve.

Both the theoretical and the experimental results point to a strong need for longer pulse experiments; some of these are already planned, and were discussed in detail. Various alternative thrusters were discussed briefly; groups working on CW laser thrusters were invited to the Workshop but were unable to attend. Systems issues were discussed only very briefly.

Double-Pulse Experiments

The overall double-pulse concept was validated by two experiments. PSI showed photographs taken with an Imacon high speed camera which clearly showed laser-supported plasmas propagating away from the surface of a glass target during the second pulse of a double-pulse sequence; a good example is reproduced in figure 2. Similar photos taken without the first evaporation pulse showed that the plasma remained attached to the target surface (figure 3). These pictures were taken with a 200 ns shutter time and a frame-to-frame interval of 1 μ s, so even though PSI used full-length TEA laser pulses, only 2 or 3 frames are taken during the laser pulse, and the LSD-wave structure is considerably blurred. Chris Rollins of PSI believes that by the third exposed frame, the LSD wave has propagated completely through the gas layer and gone out, and that the laser propagates back to the target surface and reignites a plasma on the surface. A similar photo of a target in air shows a very different structure (figure 4).

Horizontal striations visible in the PSI photos are due to PSI's absorption-emission diagnostic, diagrammed in figure 5. Photometric analysis of these photographs, and future experiments using a gated linear array detector or gated CCD, will allow calculation of the temperature and density distribution in the laser produced plasma. This diagnostic is also planned for use with larger experiments on the Scale-Up laser.

It is clear from these photographs that the gated-CCD camera now available to the Laser Propulsion Program will be invaluable. This camera will allow single frames to be taken with as short as a 5 ns shutter time. An Imacon electronic streak/framing camera would also be extremely valuable, but the cost has so far been prohibitive for the Program.

Spectra Technology, Inc. (STI) showed mass loss and impulse measurements made on lithium hydride targets (figure 6). These show clear evidence for shielding of the surface by an LSD wave during the second pulse of a pair: the mass loss at short delays (approx. 400 ns) drops considerably below that for either zero delay (a single pulse) or long delays, and approaches the mass loss observed for the evaporation pulse alone. Specific impulse and efficiency also peak at the same delay times, although the maximum efficiencies were only 10% at approximately 700 seconds Isp. The LiH targets are prepared by melting powdered LiH under argon in an aluminum foil cup; the melting is done rapidly (over a few seconds) to minimize both decomposition of the LiH and reactions with the container. Passing H₂ over a lithium foil will also make LiH, but STI reports that the mechanical properties are much worse, and the surface tends to flake off when struck by laser pulses.

The flux of the second pulse in the STI experiments is moderate (2.5×10^7 w/cm²) but the evaporation energy per unit mass of Li is so high (figure 7) that the first pulse must be at about the same flux. This suggests that either most of the laser energy is being reflected from the LiH surface, or the absorption depth is long, and most of the energy of the first pulse is remaining in the surface. The thickness of the ablated layer is only a fraction of a micron in these experiments, so it is unlikely that the absorption depth is shorter than the ablation thickness. Measurements to determine the absorption and reflection properties are urgently needed. If the evaporation energy could be reduced (by making the LiH "blackier" or by using longer pulses) the overall efficiency could be nearly doubled even if no other changes are made.

Mike Hale of STI also showed preliminary shadowgraph measurements showing the expansion of plasma away from the target surface. These measurements were made with a He-Ne laser and photodetector a few millimeters above the target surface, and provide good time resolution but only (at this point) crude spatial information. More detailed measurements of this type are planned.

Unfortunately, work at Avco Research Laboratory (AERL) with a wide variety of materials has failed to produce evidence of shielding on the second pulse. An Avco list of target materials tested is shown in table 1. The AERL small scale experiment is diagrammed in figure 8; a smoothing cell has been added to the thrust (second) pulse oscillator. The extremely clean pulse shape available for the thrust pulse is shown as an inset (figure 8b).

Delrin and related plastics, with various additives, have been the most interesting materials; they were identified as candidates at the Spring 1988 workshop, primarily because of their very short absorption length. Delrin is the DuPont trade name for polyacetal plastic (essentially polyformaldehyde, (CH₂O)_n) which has a strong resonant absorption band near 10.6 microns, probably associated with the alternating backbone C-O bond. We have so far been unable to measure the absorption length of CO₂ light in Delrin, but it appears to be less than 1 micron. This is confirmed by the near-ideal ablation behavior of Delrin, which evaporates with as little as 3 kJ/g energy input, even in 50 ns pulses.

Delrin itself has good physical properties, but is relatively unstable chemically and tends to decompose when mixed with possible seed materials containing sodium. Celcon, a similar material made by another manufacturer, has the C-O polymer chains interrupted by other chemical groups which apparently prevent the chains from "unzipping" as readily when broken. The AERL group has tried mixing various low-ionization seeds into Celcon melts, and has succeeded in getting as high as approximately 3% by number of sodium atoms into the material, in the form of 30% by weight of sodium valarate. (At the Workshop itself, this was 1% by number, Dennis Reilly provided the 3% results shortly after the Workshop). Particulate sodium, suspended in

Table 1: Targets tested by Avco Research Laboratory as of October 1988

Kapton
Delrin
Silver-loaded Delrin
Silver-dusted Delrin (surface dusted with silver flakes)
Lithium (LiOH surface contamination)
Borax + Stainless Steel Fibers
Delrin + Stainless Steel Fibers
Lithium (Clean)
Glass
Kel-F
Delrin + NaCl + Stainless Steel Fibers
Pyrophyllite + Stainless Steel Fibers
Borax + Silver Flakes
Delrin + Aluminum Flakes
Borax + Aluminum Powder + Carbon Black
Delrin + Aluminum Paste + NaNO_3
Delrin + Silver-coated Spheres
Delrin + Aluminum Powder
Celcon + Aluminum Paste + Sodium Dispersion (10 μm particles in oil or wax)
Celcon + Aluminum Stearate + Aluminum Paste
Delrin + Silver-coated Glass Fibers
Sodium Suspension
Celcon + Silver-coated Glass Spheres
Celcon + Nickel-coated Graphite Fibers

wax, can also be mixed in, but the particle size is several microns, and presumably this does not produce a uniform distribution of seed in the evaporated material.

Even at the highest concentrations of low-ionization seed, Delrin/Celcon targets continue to show Q^* values essentially independent of the laser pulse spacing for double pulses. The AERL group interprets these results as indicating that LSD waves are not propagating in the C-H-O vapor, and thus not shielding the target surface, during the 50 ns pulses used. From single-pulse tests in air it is clear that the laser fluences used are sufficient to ignite an LSD wave and produce at least some shielding; we do not yet understand why there is no shielding with double pulses in vacuum. PSI modelling results (see below) suggest that the experiment conditions are marginal for shielding, and that longer pulses and/or higher fluxes will be needed. However, these results are clearly preliminary, and more detailed models and more extensive experiments will be needed before the models can be considered reliably predictive.

AERL has had better results on controlling LSD-wave ignition properties. Over the past several months, the AERL group has succeeded in mixing various forms of metal flakes, wires, and metal-coated glass spheres and fibers into Delrin and Celcon melts. The improved ignition properties of these mixtures were demonstrated using single pulses in air; the mass removed from the metal-loaded targets is up to tenfold less than the mass removed from plain targets (figure 9). Microscopic examination of the targets confirms that the surface is relatively undisturbed; i.e., the

reduced mass loss is not simply due to an accumulation of hard-to-evaporate metal or glass on the surface. There is also evidence from a fast photodiode detector that the plasma "lights off" promptly (within a few ns) on the seeded targets, while there is a delay of up to 20 ns on the unseeded targets at total fluences below approximately 10 J/cm.

The AERL group has recently been using a simple extrusion process to orient metal-coated fibers in plastics, as a way to approximate the "Tuned Ignition Array" of 5-micron stripes proposed by Dennis Reilly. Ideally, a thin conducting film on a roughly 10 micron fiber, seen end-on, will act as an efficient antenna for 10.6 micron radiation and concentrate the incident energy into the small volume of the film. The exact mechanism for producing ignition from such "resonant" structures remains unclear; it may be associated with electron field emission due to high E fields, or with vaporization of the film (and associated high temperatures and pressures) due to high current flows. In either case, the appearance of a significant effect at fluences as low as 1 J/cm² implies that we should be able to ignite LSD waves efficiently on dielectric targets loaded with suitable metallic or metal-coated particles.

One interesting phenomenon observed at AERL is wavelength-scale surface ripples that appear surrounding coated fibers after a laser shot. Dennis Reilly interprets these as optical interference fringes, reproduced in the surface contour by variations in ablation rates; if so, they may serve as a diagnostic for the interaction of the laser pulse with the fiber. This interpretation was challenged, however, by Arthur Kantrowitz at the Workshop, who pointed out that the ripples could be capillary waves of some sort.

DOUBLE-PULSE THEORETICAL/MODELLING RESULTS

The only groups reporting new theoretical and computational results at the Workshop were PSI (represented by several researchers) and Stanford. The NRL Computational Physics group (Elaine Oran et al.) ceased working for the Program earlier in the year, and was not represented.

Chris Rollins briefly reviewed PSI's past work. This included work on propellant selection, which has led to their use of glass (especially soda-lime glass, SiO₂ + Na₂O + CaO) as an experimental test material, and on various modelling codes. Their initial modelling of repetitive pulse effects has led to the concentration of the entire Program on short absorption length materials. They now have the ability to model essentially the entire double-pulse process in 1- and 2-D, except for the details of the ignition process, using a variety of propellants (H₂O, CH₂O, SiO₂, LiH, etc.). However, several aspects of this model, especially the chemical kinetics, are relatively crude, and the full models are relatively time consuming to run.

PSI has therefore concentrated on a simple 1-D steady-state model for a propagating detonation wave, illustrated in figure 10. By treating the detonation wave velocity D as fixed, the problem becomes time independent, and the properties of the wave become numerically integrable functions of the distance Δx behind the shock front. The computation is fast enough to lend itself to numerical experiments covering many materials and parameter values. One example is shown in figure 11. The curves in each plot show the variation of several variables (pressure, density, temperature, absorption coefficient) behind a shock in water vapor. The laser intensity and other initial conditions are fixed, but the amount of low-ionization seed (lithium vapor) present is varied from .03% to 3%.

The key feature of this calculation can be seen best in figure 11d, which shows where the laser energy is absorbed. Just behind the shock, the temperature is roughly 6000 K, hot enough to ionize the Li seed, but not H or O atoms. Without any seed, the beam is absorbed only weakly. The 0 seed curve is not shown on this plot because the absorption remains near zero for about 2 mm, three times the width of the plot. Only after this distance is the weak absorption enough to raise the temperature to the point of appreciably ionizing the gas, increasing the absorption and the temperature further. This positive feedback generates quickly creates a zone of strong absorption 2 mm behind the shock front. Adding a small amount of seed shortens the "weak absorption" zone drastically, and the absorption peak occurs only 1/2 mm behind the shock. As the amount of seed increases, the weak absorption zone continues to shorten, until at high seed concentrations the temperature jump at the shock itself produces enough electrons from ionized Li to absorb the laser directly, with no ionization of the propellant itself.

Although the distances shown in figures 10-13 are small, the density jump behind the strong shock means that a substantial amount of mass is involved in the LSD wave. For the seedless case, this amount is 3.5×10^{-3} g/cm², corresponding to 1.75 cm of unshocked vapor (at 2×10^{-3} g/cm³, or slightly above atmospheric density). Clearly, in our 50 ns experiments, which typically evaporate less than 100 μ g/cm² of propellant, the LSD wave will not approach its steady state if no seed is present. Even if the propellant contains substantial seed (1%) there is barely enough mass present to establish the LSD wave. Even without detailed modelling of the transient conditions, it seems unlikely that the LSD wave will form and shield the propellant surface unless there is a very high concentration of seed (e.g., the 50% number density of Li in LiH). However, in longer-pulse experiments, shielding would occur even at low seed concentrations.

Figure 12 shows a set of steady state calculations for lithium hydride at much lower flux (5×10^6 vs. 9×10^7). Despite the reduced flux, the characteristic distances involved are less than lithium and the higher vaporization temperature of LiH compared to water. The "cold gas" temperature ahead of the shock is 3000 K rather than 600 K, so even with a much weaker shock the temperature behind the shock is comparable to that for water vapor.

These results agree with what has been observed experimentally. However, they do not account for the observed shielding with even 50 ns pulses in air. At the Workshop, Arthur Kantrowitz and others noted that the model used is a single-temperature model. It may thus substantially miscalculate the electron temperature and number density, probably underestimating n_e and overestimating the difficulty of propagating an LSD. If so, shielding should take place within 50 ns, and the failure to see shielding with seeded plastics may be a result of peculiarities of the plastic vapor (e.g., strong electron attachment to some species preset) or to transient effects; the initial formation of a uniform absorbing plasma and creation of an LSD wave may take considerable time. The steady state calculation is also sensitive to the detonation-wave velocity, and hence to both the propellant vapor density and the laser flux. The vapor density, in particular, has not been directly measured in experiments, and may vary drastically in the region just above the solid surface. The steady-state calculations are thus useful mainly for quickly exploring the qualitative effects of various propellants, seeds, laser fluxes, etc.

Prof. Chang of Stanford University, and his student Jim Mulroy, presented results from 2-D fluid dynamic modelling of the expansion around the base of a conical vehicle, starting with an initial slab of laser-heated gas (ideal gas, $\gamma = 1.2$) expanding into near-vacuum. Their current calculations use a NASA Ames 2-D Eulerian code for unsteady flow with a shock-capturing TVD scheme running on a Cray X-MP. The primary goal of this work was to determine the effect of a finite base size on thrust efficiency. The results for total impulse vs. time are shown in figure 13

for various aspect ratios A , where the aspect ratio is the ratio of the base diameter to the thickness of the initial gas slab. Unfortunately, some of the calculations presented did contain errors, notably a lack of agreement between computed curves for high aspect ratios and an analytic calculation for the 1-D (infinite aspect ratio) case; this is visible in figure 13, although it is clearer in, e.g., calculations of centerline pressure. Thus there is some reason to doubt the absolute accuracy of figure 13. However, even these preliminary results indicate that an $a=8$ case (approximately what we expect to have in the SCALEUP experiments) will give 60% to 80% as much total impulse as an arbitrarily high aspect ratio would.

SCALE-UP EXPERIMENT

Dennis Reilly of AERL gave an update on the current status and plans for the Scale-Up 2 kJ experiments. These experiments involve converting the AERL Scale-Up excimer laser into an e-beam pumped CO_2 laser. The final design, sketched in figure 14, uses four independent 10" diameter cavities, operated as stable resonators with 70% reflective coated salt windows. The experimental vacuum tank is mounted directly to the end of the laser, so the same windows serve as the entrance windows for the tank. Simulation and tests with a small laser give an expected energy output of roughly 600 J/beam in a nominal 1 μs pulse.

The beams are focussed and overlapped by four copper mirrors; the beam profiles and energies are diagnosed by arrays of pyroelectric detectors mounted in these mirrors. The nominal focal spot is 8 cm in diameter, giving a fluence of at least 40 J/cm², but the focusing mirrors can be moved to give any desired spot size. Two 250-J TEA laser modules, on loan from NRL, will provide the evaporation pulse; with beam shaping and optics losses approximately 300 J will be available for ablating propellant.

AERL will provide diagnostics for target mass loss, total impulse, and pressure at the target surface. The pressure sensors will have response times of approximately 1 μs , which should show major deviations from ideal gas expansion. AERL will also do through-target transmission measurements to measure the onset of LSD-wave shielding, and will use an LLNL-supplied 5 ns gated intensified CCD camera to photograph LSD wave phenomena on both normal and microscopic scales. PSI will supply a two-channel surface radiometer and a four-channel plasma radiometer, plus their emission/absorption diagnostic for plasma temperature and density. Other diagnostics, including interferometers and shadowgraphs for observing the cold gas density before the second pulse, are under consideration.

OTHER EXPERIMENTS AND EXPERIMENTAL PLANS

Lehigh University

Prof. Yong Kim of Lehigh University reported on his progress in setting up experiments using vapor-deposited targets. The target-deposition system is capable of depositing a variety of target materials on a liquid-nitrogen cooled plate, including water vapor and aluminum vapor. Targets can be formed either in layers or, by operating several deposition sources at once, as fine-scale mixtures of materials. Targets are currently illuminated by a single Nd:YAG laser with a pulse energy of approximately 20 J and a pulse width of 20 ns; a second YAG laser is available for double pulses.

A portion of the incident YAG laser pulse is split off and focussed on a steel target near the actual target, producing a broadband laser-plasma "flashlamp" for spectroscopy. Using a gated OMA (optical multichannel analyzer), Prof. Kim has observed spatial density profiles in benzene vapor (benzene being used to provide a convenient strong absorption line). Prof. Kim is also completing a small laser-diode interferometer for density measurements, and is continuing to develop fiber optic sensors capable of measuring the plume temperature.

Finally, Prof. Kim presented plans for a direct measurement of energy absorption in the propellant, refining a concept suggested over the summer by Jordin Kare. A thin metal film deposited on a substrate serves as a thermometer, and a thin (1 - 10 micron) layer of propellant is deposited over this. By measuring the temperature rise at various depths into the propellant block, it should be possible to directly measure the absorption depth of various materials; the time resolution is sufficient to allow, e.g., separate measurement of energy deposited by the evaporation pulse and by reradiation from an LSD-wave plasma during the second pulse.

University of Washington

Prof. Robert Brooks of the University of Washington gave a brief talk on his progress in adapting a large (up to 1 kJ) e-beam CO₂ laser to Laser Propulsion Program work. He was unable to get a sufficiently uniform beam from the laser using the existing unstable resonator, and has put in a multimode flat-flat resonator (a concave mirror will be installed soon to give a true stable resonator). The resulting beam has some overall variation in intensity, but is locally quite smooth. The pulse shape is similar to a standard TEA laser pulse; the pulse energy is currently only about 200 J due to capacitor limitations.

Prof. Brooks showed some initial streak camera photographs of LSD waves formed above aluminum targets in air. These indicated relatively low LSD-wave velocities (<3 mm/ μ s) and considerable millimeter-scale variations in the LSD-wave brightness, presumably due to beam variations. Prof. Brooks has two 100 J TEA lasers available, and some possibilities for configuring the large laser as an amplifier and getting longer, more uniform pulses, or at least suppressing the gain-switch spike, were discussed.

Lawrence Livermore National Laboratory

Jordin Kare of LLNL reported on tests of the "dimpled-plate" concept for coupling laser energy to air. A copper plate was machined with a simple spherical end mill to have many overlapping "dimples", roughly 5 mm across. The plate is illuminated in air with approximately 10^7 w/cm² from a Lumonics 103 TEA laser (approximately 40 J in 1 μ s). Each dimple acts as a roughly f/1 reflector, focusing the laser beam at a point a few mm above the surface and creating a clean-air breakdown. These breakdowns then grow, both toward and away from the reflector surface; depending on the laser flux, the propagation can be either supersonic (LSD wave) or subsonic (LSC wave). With sufficiently long pulses, the plasmas should merge to completely shield the surface; for the pulses (and dimple scale) used, the plasmas remain separated, but ideally still couple most of the laser energy to the air, since the surface is highly reflected.

The observed threshold for breakdown (using pyroelectric detectors viewing through a pinhole in one dimple) was roughly 1.5×10^7 w/cm² incident on the surface; this was not enough to create breakdowns at the surface, and photographs clearly show multiple plasmas floating above the plate (figure 15). The breakdown did take some 10 to 20 ns to become opaque (figure 16), and so considerable energy in the TEA laser gain spike is lost. Also, measurements of scattered and reflected light indicate that a substantial amount of light is being scattered by some

mechanism; whether by reflection or refraction from the plasmas themselves, or by scattering from the plate and transmission through the plasmas, is as yet unclear. Tests with single dimples and more extensive diagnostics are planned.

Impulse measurements on the dimpled plate gave coupling coefficients for the bare plate (with a 3.5 cm diameter laser spot) of up to approximately 10 dyne-s/J. Adding a simple 5 cm long skirt to contain the expansion raised the coupling coefficient to 15 dyne-s/J. This is still considerably below the 50-100 dyne-s/J which should be possible with an air-breathing system, and no effort was made to test or control the refresh time (delay until fresh air is available for a new pulse) which will limit the performance of a real air-breathing thruster. However, the simplicity of the dimpled plate is appealing, and several Workshop participants suggested variations, including Arthur Kantrowitz's suggestion of spatially grading the composition of a rocket propellant to create "self-forming" dimples in the surface.

RELATED CONCEPTS

There were several presentations on concepts outside of the main thrust of the Laser Propulsion Program. Leik Myrabo of RPI discussed his "Lightcraft Technology Demonstrator" (figure 17), an integrated single-stage-to-orbit vehicle which operates as an air-breathing scramjet up to approximately Mach 7 and 40 km altitude, then converts to a liquid-nitrogen-fuelled rocket mode to reach orbit. Once in orbit, the laser concentrating optics are assumed to double as optics for a reconnaissance system. The LTD is scaled to match a 100 MW laser system, and has been designed to use standard hardware in ingenious ways; e.g., the nitrogen is used for cooling in air-breathing mode and as propellant in laser rocket mode, and the ullage is allowed to evaporate, providing a high pressure gas reservoir for cold-gas attitude control. However, the design makes a number of assumptions about, e.g., the attainable I_{sp} of an N_2 rocket and the utility of nonimaging optics, that remain to be proven correct.

James Erler of SAIC provided a short review of the GEDI program, which proposes the use of ablative laser propulsion to steer a small, lightweight (10 cm, 10 g) projectile launched at ≈ 100 km/s by an electromagnetic accelerator. While the system parameters are very different from those for double pulse propulsion, some of the questions of guidance system stability are closely related.

Philip Chapman of Space Energetics, Inc., spoke briefly on possible SDI and other missions for laser propulsion.

Although PSI did not make a separate presentation on the subject, the possibility of operating a laser propulsion thruster in a long-pulse, quasi-steady-state mode was discussed. This possibility is based on PSI's observation of high efficiency (15%) and specific impulse (600 - 800 seconds) thrust produced with 24 μ s pulses on carbon composite targets. PSI has continued to do some modelling of this mode, which is believed to involve the formation of a stable, partially-absorbing laser supported plasma above the target surface. It is of interest both for its possible simplicity (single pulses; compatible with "standard" e-beam CO_2 lasers) and for its possible compatibility with rf-linac FEL's, which naturally operate in a quasi-CW mode.

Finally, Jordin Kare of LLNL discussed the possibility of using a single ground-based laser site to do certain types of orbital maneuvering. A two to five megawatt laser with a 4-meter scale telescope would be capable of many missions, including raising the orbits of Space Shuttle External Tanks and, possibly, injecting large satellites into geosynchronous transfer orbits. Such a

system would require a concentrator on the space vehicle, and would be in direct competition with other orbital maneuvering systems such as solar-thermal, solar-electric, and even laser-electric propulsion. However, the capital cost of the ground portion of such a system would be relatively low (\$50 M), and the laser would also be useful for various tests of atmospheric transmission, etc., as well as for demonstrating ground launch of small "sounding rockets." The question remains open whether a "detour" into such orbital maneuvering would aid or damage the overall progress of the Laser Propulsion Program toward a ground-to-orbit launch capability.

DISCUSSION AND CONCLUSIONS

Several things are clear from the results presented at this Workshop, and from extensive discussion. First, the double-pulse concept works. From STI's results on LiH and PSI's results on glass, it is clear that LSD waves can be propagated through an evaporated layer of propellant, and that increased specific impulse and efficiency can be obtained compared to putting the same energy in a single pulse. However, it is also clear that continuing more or less blind trials with small lasers and short pulses, described at various times as an "Edisonian" approach, cannot be expected to yield thruster efficiencies much higher than 10% to 15%. We understand enough to expect to do better with brute force -- in particular, with longer laser pulses -- but not enough to explain quantitatively what our current experiments are telling us.

The Workshop seemed to accept that the double-pulse thrust cycle can be understood best as having four essentially separate phases: ablation, LSD-wave ignition, LSD-wave propagation, and expansion/recombination. A fifth area of concern, not really part of the cycle itself, is rep-pulse effects, which can be taken to include things that happen in the interpulse time between pulse pairs.

Ablation is, particularly in the view of Chris Rollins of PSI, well understood in general, as a result of extensive work in other programs. Given a few values (absorption depth, pyrolysis rates, and standard material properties) the ablation process can be accurately modelled for single or multiple pulses. Unfortunately, the necessary values are not in general available for the materials we are interested in, and are not trivial to measure. Also, the exact chemical and physical composition of the ablated material may be critical for laser propulsion -- for example, the degree to which metal particles are evaporated before they can cause premature breakdowns above the surface -- and this may not be adequately modelled by codes designed for laser damage work. From PSI's rep-pulse work and general experience with short pulse experiments, it is clear that the absorption depth is particularly crucial, and must be measured experimentally for propellants of interest.

LSD-wave ignition remains essentially beyond the capability of computer modelling. Guy Weyl's analytic work on ignition from metal flakes is useful as a guide, and some analysis of the detailed electromagnetic behavior of wavelength-scale metal structures is needed. However, the AERL results in air, and the relative ease with which AERL has fabricated propellants with metal films oriented by extrusion, suggest that ignition will not be a serious problem at 10.6 microns. Metal flakes work, and produce ignition at fluences of order 1 J/cm^2 in times of a few ns.

Propagation, and particularly the transition from isolated plasma ignition sites to a propagating LSD wave, has proved to be a major problem. This is contrary to our earlier assumptions that propagation of LSD waves would be straightforward, given a sufficient density of ignition sites and a high enough flux. PSI's current modelling efforts seem to be sufficient to indicate directions for propellant design. They are clearly not sufficiently detailed to give reliable

quantitative predictions, but blind efforts to include all possibly-relevant physics (e.g., multiple temperatures, chemical dissociation and ionization rates) would probably be unproductive, especially as some input values are unknown. Thus the current need is for quantitative comparison of calculation with experiment, so that improvements in the codes can be made as needed.

The main problem with the expansion phase continues to be that chemical reaction rates are simply not available for the conditions of interest. PSI has used very simple chemical kinetic models with extrapolated reaction rates to conclude that some chemical bonds (notably C-O bonds) will reform, but the amount of energy which will actually appear as exhaust kinetic energy is unknown. The percentages of recombination are also sensitive to the initial conditions of temperature and density behind the shock, so PSI's results can again be considered only as guidelines, pending experimental checks. Prof. Kantrowitz has proposed affecting recombination rates by introducing "catalysts", perhaps in the form of carbon or some other refractory material which would condense to particulates in the exhaust. Unfortunately, no way of predicting the effects of such additives has been suggested. The current success with lithium hydride makes the notion of using light hydrides with inherently low dissociation energies more appealing.

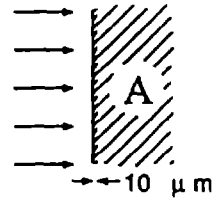
The general conclusion of the Workshop can, I believe, be stated as a call for longer pulses and better diagnostics. Longer pulse experiments will allow us to get out of the transient regime and observe steady-state LSD-wave propagation in a much wider range of materials; the increased mass per unit area involved will also relax the severe constraints on absorption depth in the evaporation phase. We expect significantly better efficiencies with longer pulses as well. Better diagnostics will give us a much clearer understanding of what is happening in both existing and larger-scale experiments; the value of a fast camera system was clearly illustrated by the impact of PSI's handful of framing-camera pictures, even though they were taken under marginal conditions.

Finally, some specific experiments were proposed to try to simplify the experimental system and thus gain a better check against theory; the foremost of these was to do simple LSD-wave propagation experiments in uniform atmospheres of various gases, such as C-H vapors, nitrogen, and water vapor, to try to understand the difference between AERL's results in air and in Delrin vapor. These experiments are now being planned, in varying forms, by all of the experimental groups; in the next six months to a year, we should see a much-increased experimental understanding of the properties of the double-pulse thruster system.

Figure 1: Double-Pulse LSD-Wave* Thrust Cycle

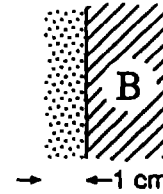
A) "Metering" pulse evaporates a thin layer of propellant

$$\tau_1 = 2 - 5 \mu s$$

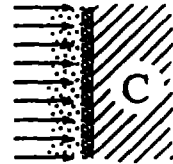


B) Gas expands to the desired density

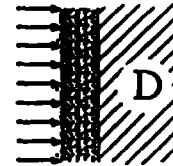
$$\tau_{1-2} = 0 - 5 \mu s$$



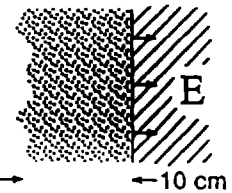
C) Main pulse passes through gas, forms plasma at surface $\tau_{\text{ign}} = \text{few ns}$



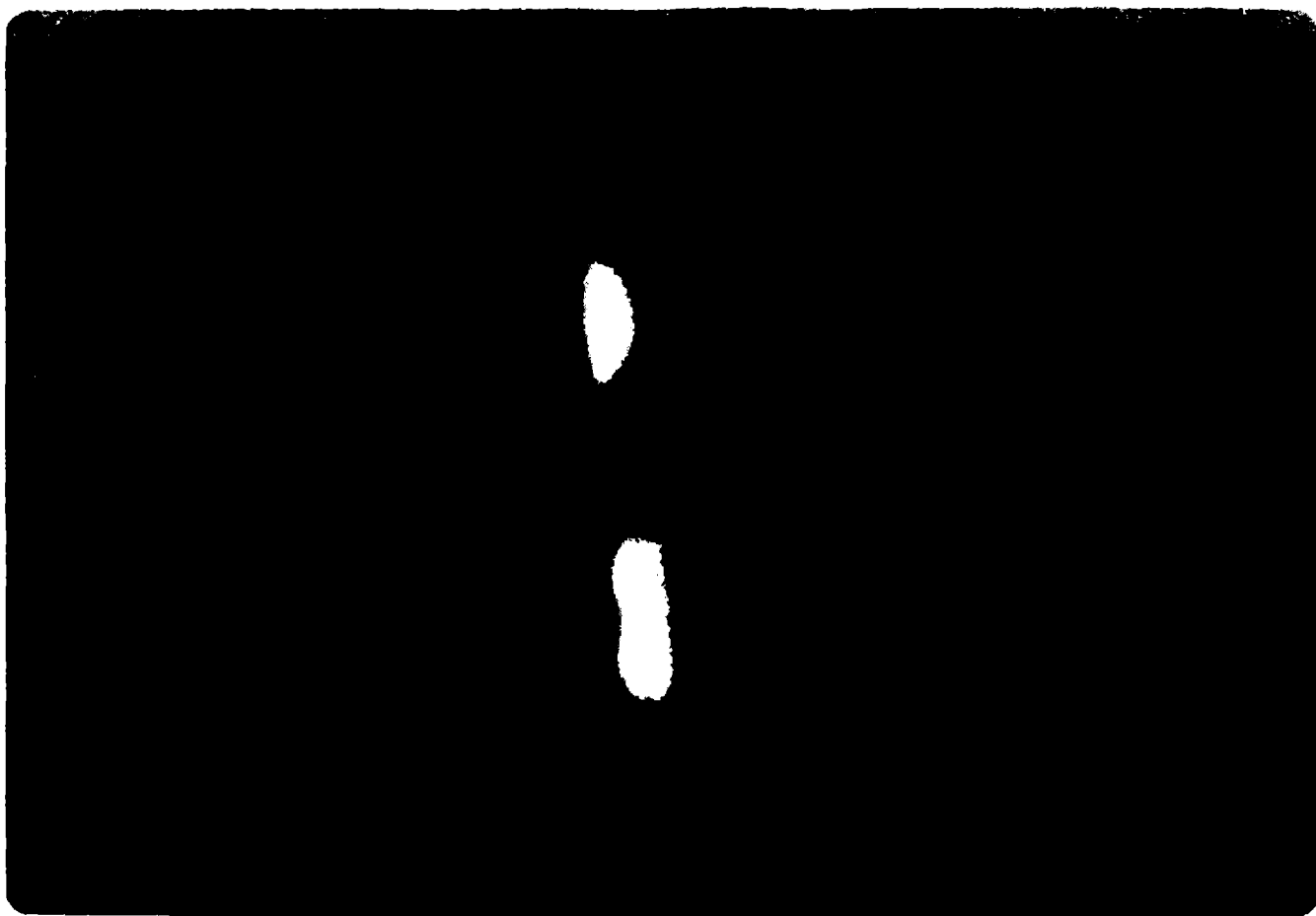
D) Plasma absorbs beam by inverse bremsstrahlung; absorbing layer (LSD wave) propagates through gas $\tau_2 = 1 \mu s$



E) Uniformly hot gas expands in 1-D, producing thrust $\tau_{\text{exp}} = 3 - 10 \mu s$



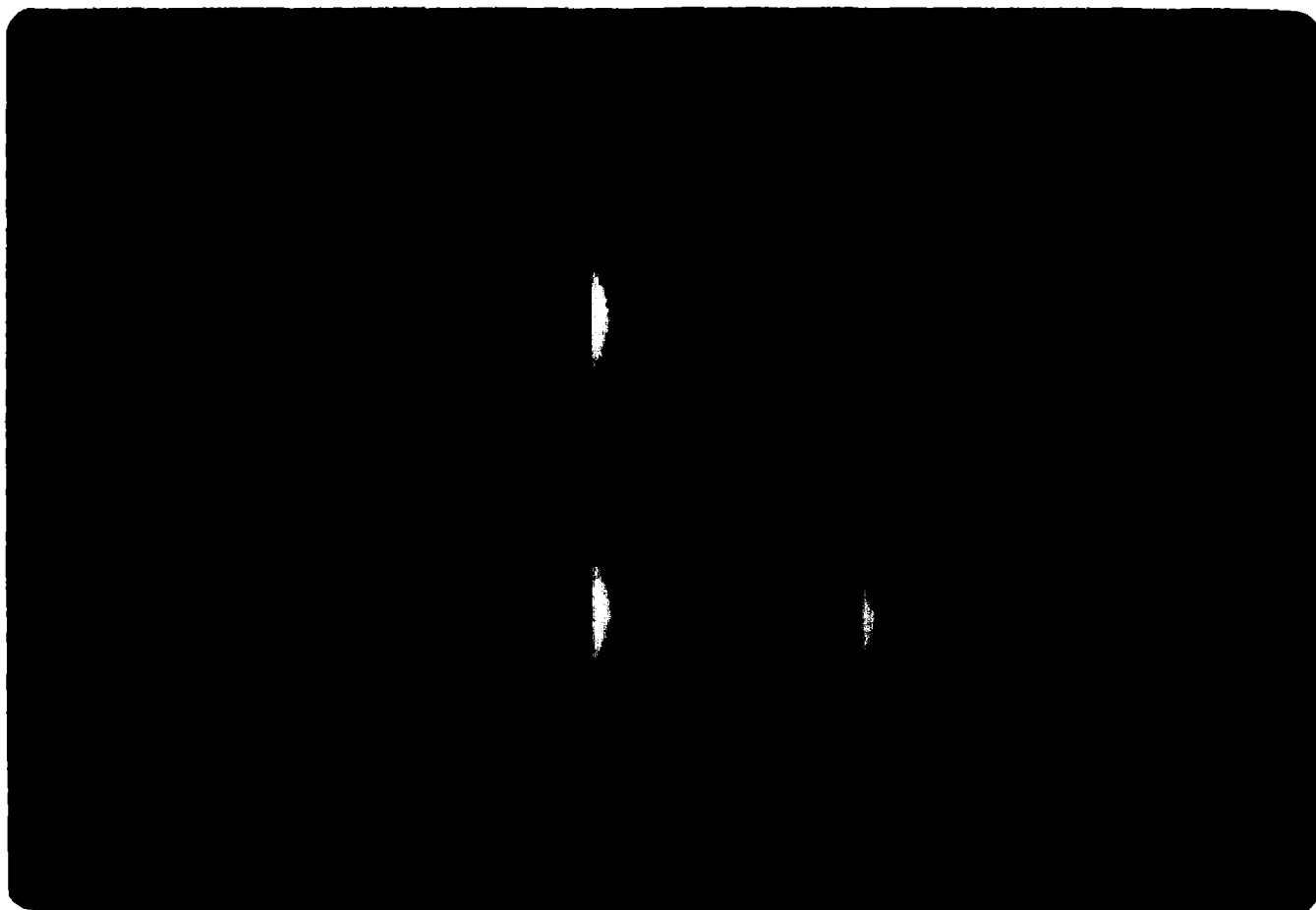
F) Exhaust dissipates; cycle repeats at 100 Hz - few kHz



Self Transmission Framing Photo for Double Pulse Experiments on Glass

Frame Separation = 1 μ sec

Pulse Separation = 5 $\frac{1}{2}$ μ sec



Self Transmission Framing Photo for Double Pulse Experiments on Glass

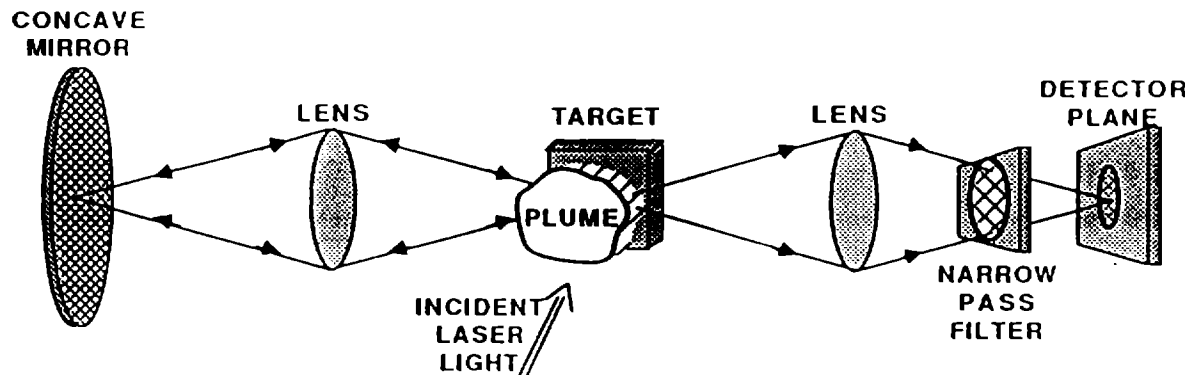
Frame Separation = 1 μ sec

Pulse Separation = 0



Self Transmission Framing Photo for Single Pulse Experiment on Glass
in $\frac{1}{2}$ Atmosphere Air Background

Figure 5: PSI Plasma Self-Transmission Diagnostic



A-8008

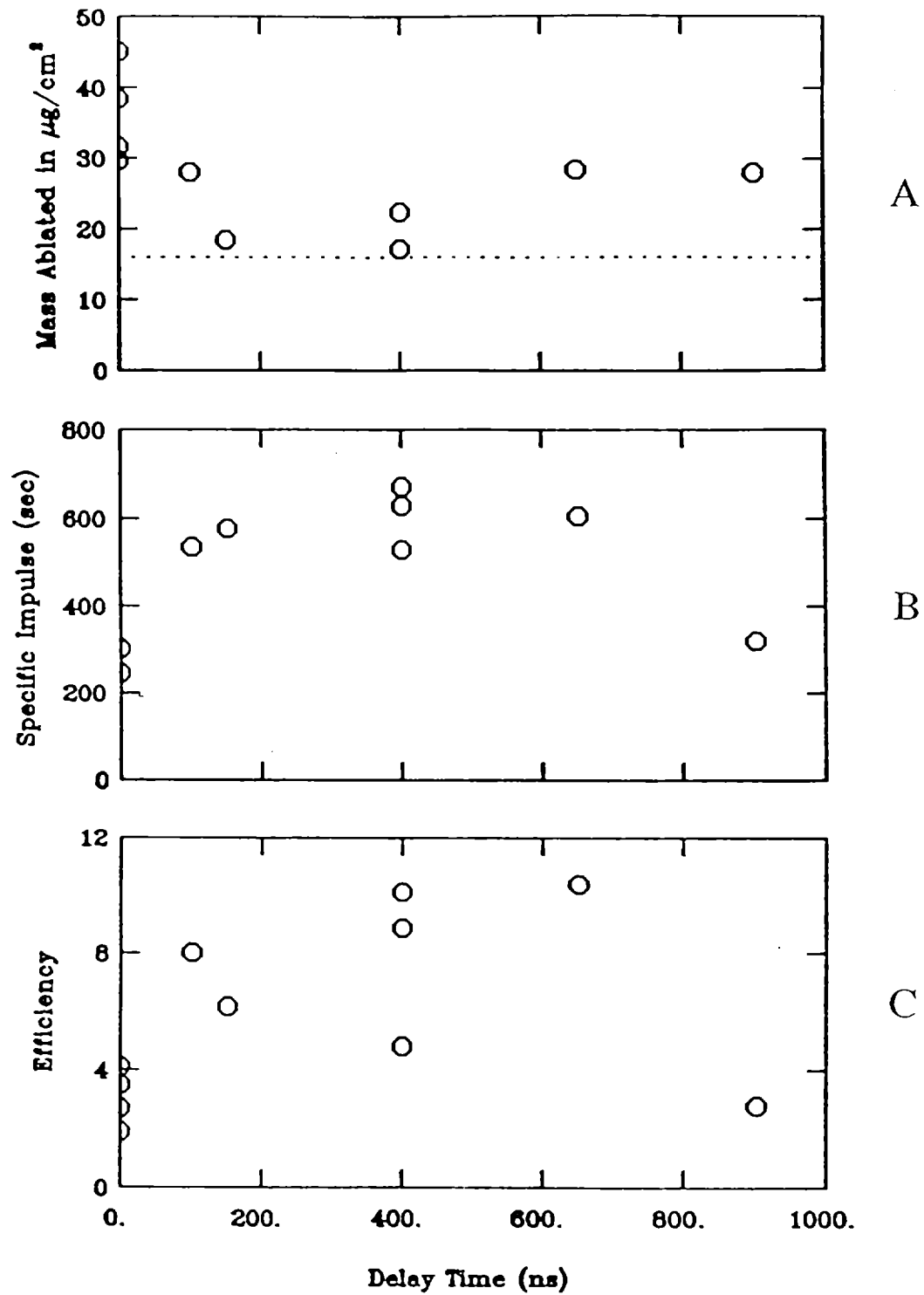
1) GIVES SPATIAL PROFILE OF PLASMA TRANSMISSION

2) RATIO OF EXPOSURES, BRIGHT TO DARK: $\frac{E_B}{E_D} = 1 + t^T$

WHERE: t = TRANSMISSION OF OPTICAL SYSTEM
 T = TRANSMISSION OF PLASMA

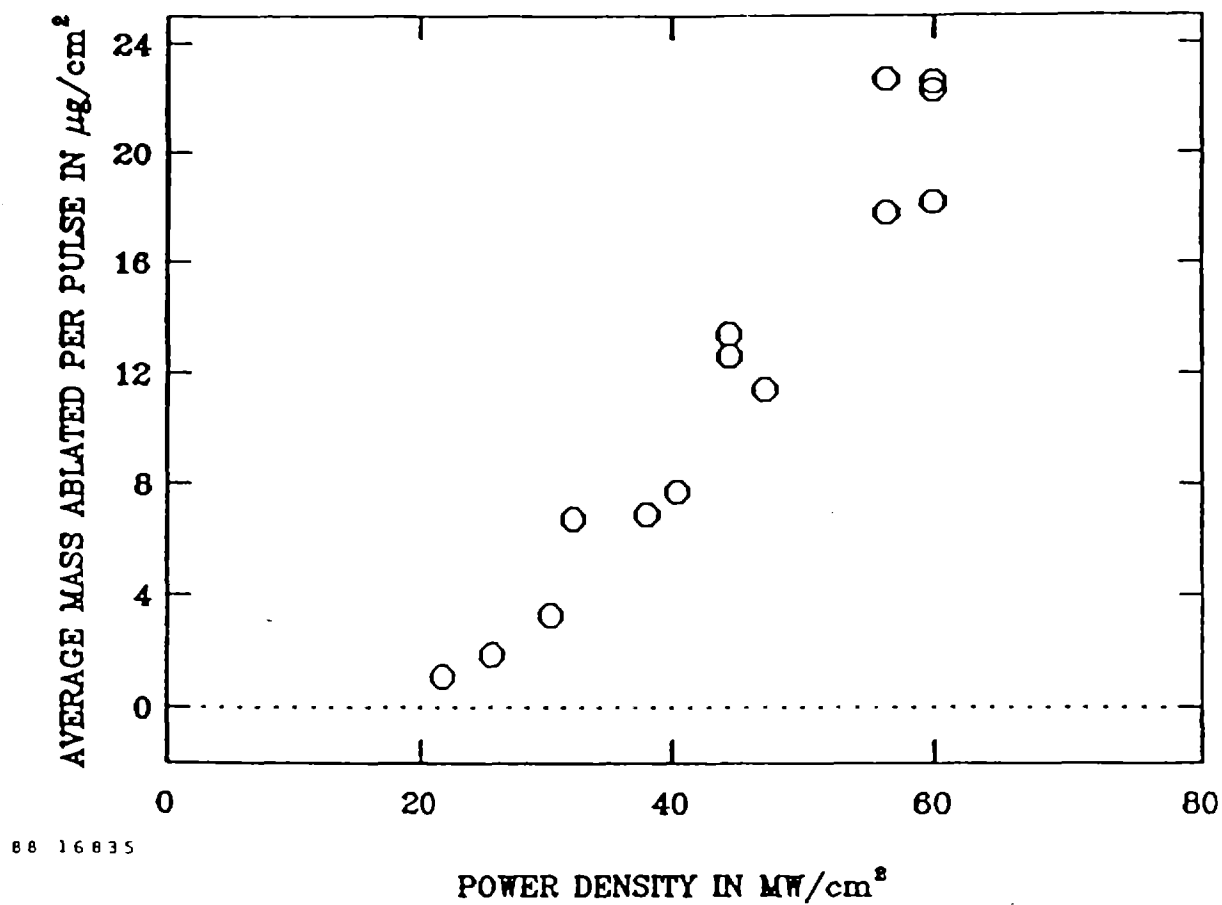
3) USE $K_\lambda \ell = \ln T$ TO FIND ABSORPTION COEFFICIENT
 \Rightarrow CAN DEDUCE TEMPERATURE DISTRIBUTION

Figure 6: Double Pulse Tests on LiH



Spectra Technology, Inc. (STI) measurements on polycrystalline LiH in vacuum. Both pulses are approx. 70 ns long at 25 MW/cm². Delay Time is the interval between the first and second pulses. Values at long times are comparable to values at 900 ns. Dotted line in (A) shows mass loss measured for first pulse alone.

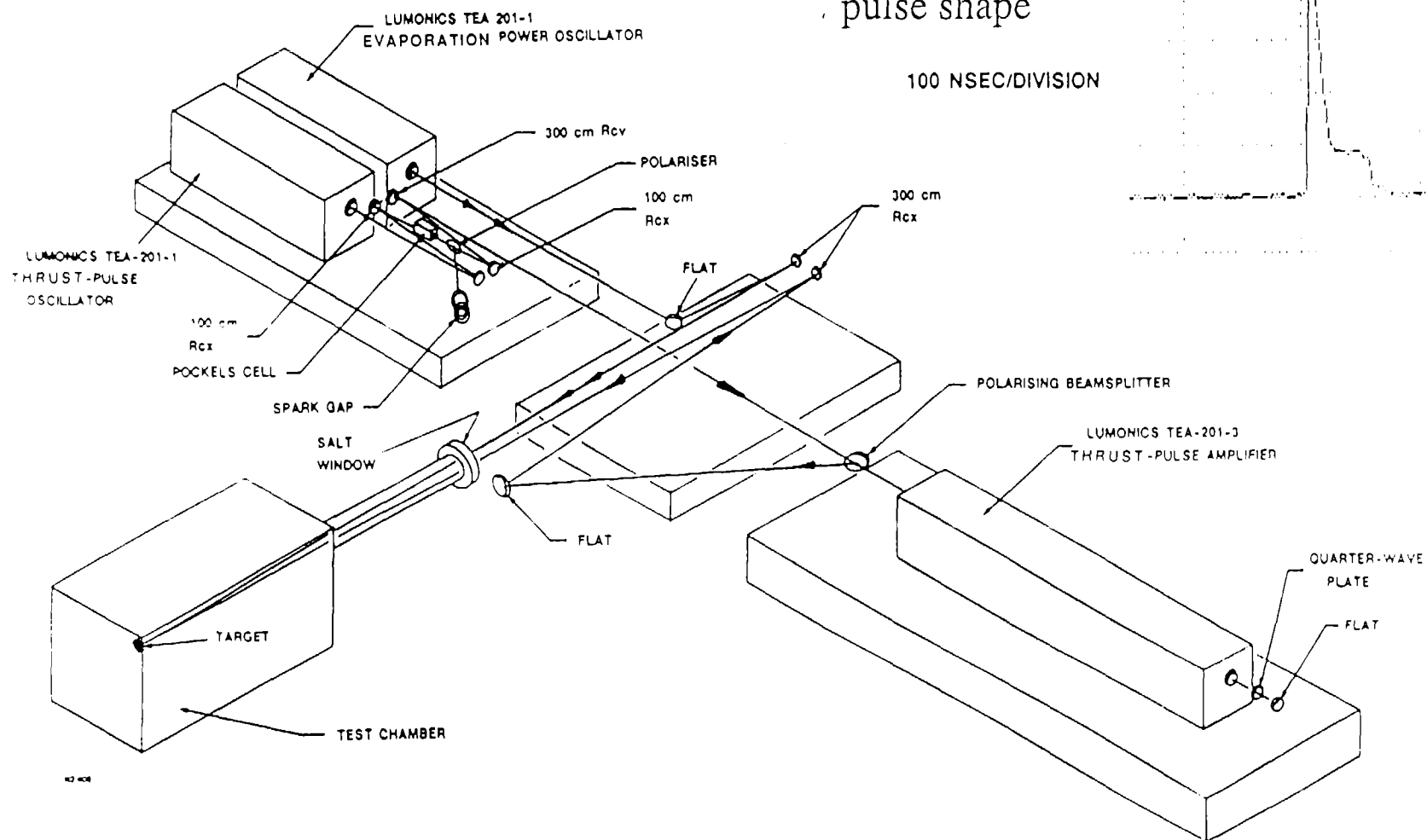
Figure 7: Single Pulse Ablation of LiH



STI measurements on polycrystalline silicon in vacuum. Laser spot area is approx. 3 cm². Laser pulse width approx. 70 ns. High threshold suggests that absorption depth is long.

Figure 8: Avco Small Scale Experiments

A. Experiment layout



B. Thrust (second) pulse shape

100 NSEC/DIVISION

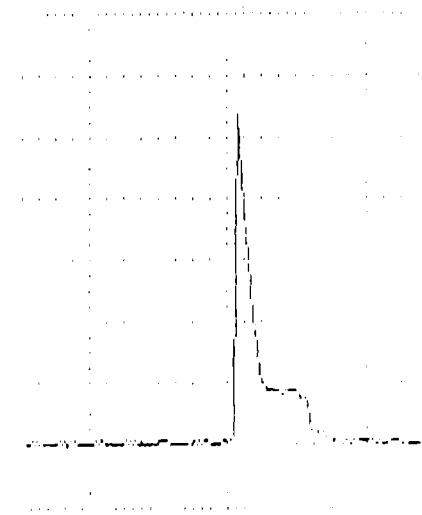
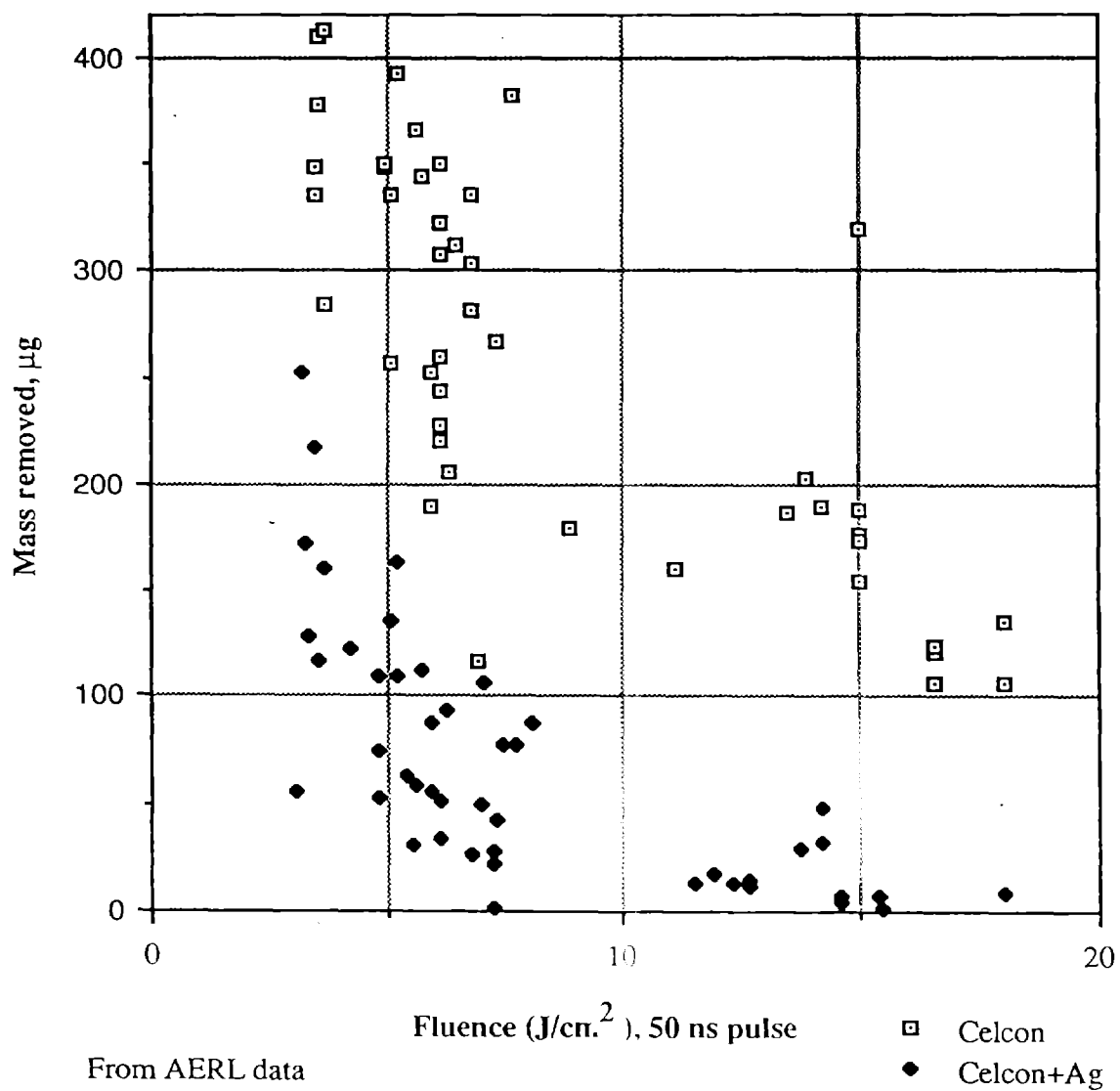


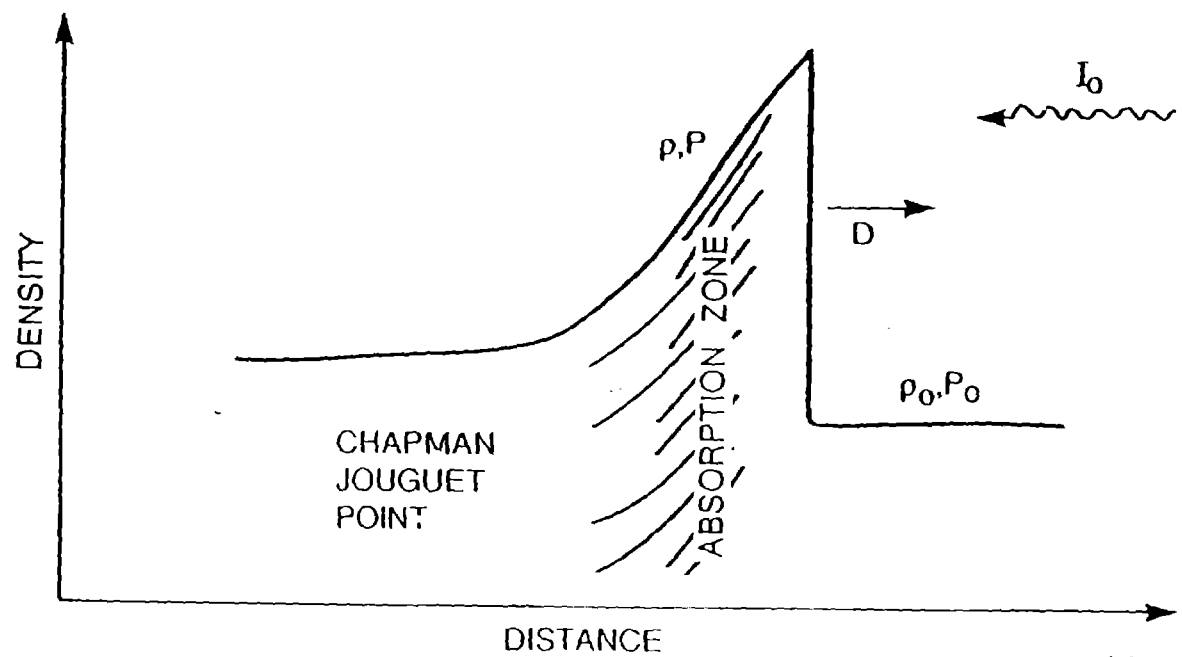
Figure 9: Reducing Mass Loss by Adding LSD-wave Ignition Sites

Adding approx. 20% silver-coated glass microspheres to Celcon plastic
reduces mass loss from a single laser pulse in air by up to 10 fold



From AERL data
8/13-14/88

Figure 10: Propagating LSD-Wave Structure



A-8486

Figure courtesy PSI

Figure 11: Effect of Li Seed on LSD Wave in Water Vapor
(PSI 1-D steady state calculation)

A. Pressure

$$I = 8.8 \times 10^7 \text{ (W/cm}^2\text{)}$$

$$P_0 = 5.30\text{E}+00 \text{ atm}$$

$$T_0 = 6.00\text{E}+02 \text{ }^\circ\text{K}$$

$$\lambda = 10.6 \text{ } \mu\text{m}$$

$$\rho_0 = 2.00\text{E}-03 \text{ g/cm}^3$$

$$D = 8.00\text{E}+05 \text{ cm/s}$$

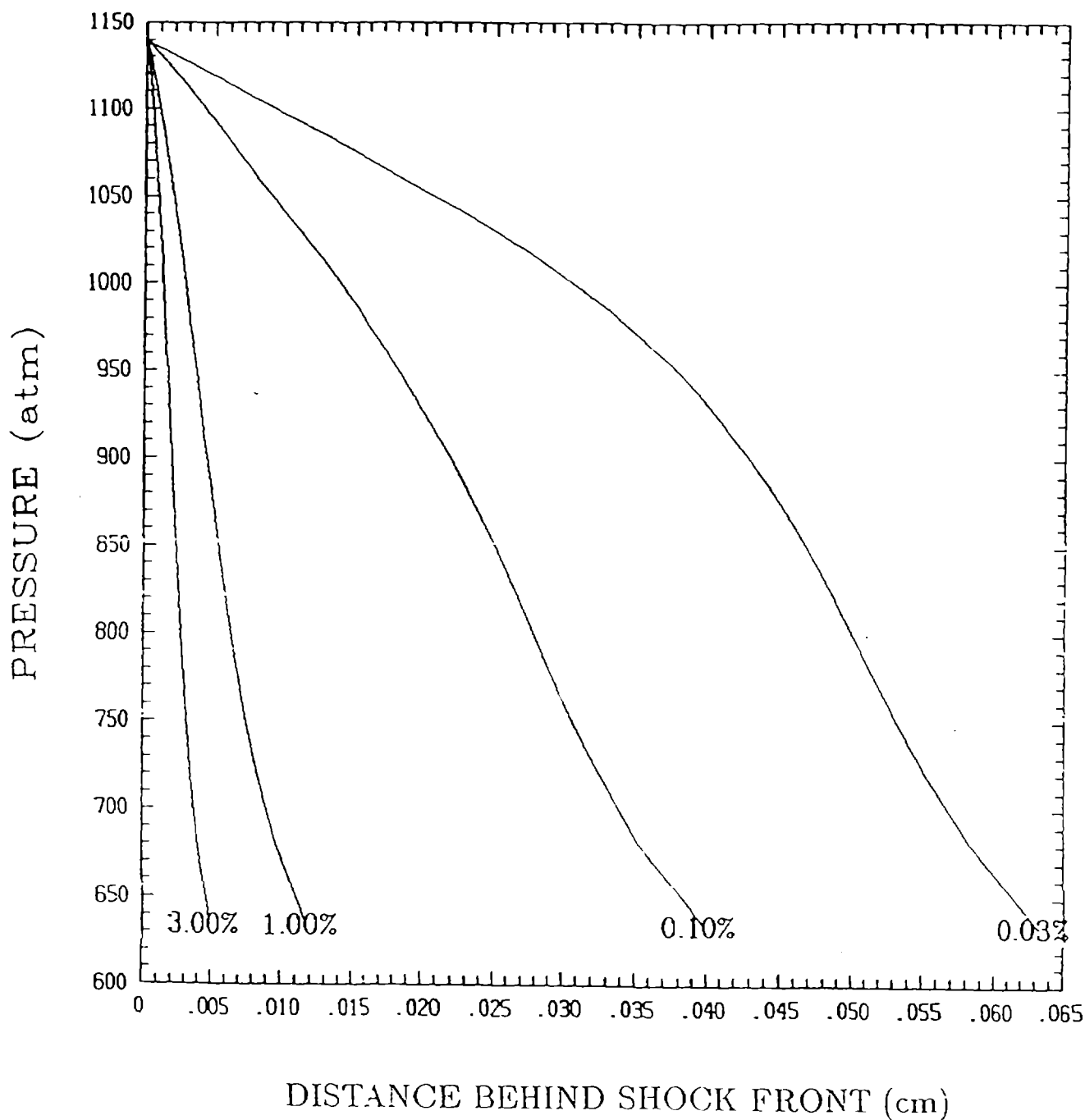


Figure 11: Effect of Li Seed on LSD Wave in Water Vapor
(PSI 1-D steady state calculation)

B. Density

$$I = 8.8 \times 10^7 \text{ (W/cm}^2\text{)}$$

$$P_0 = 5.30\text{E}+00 \text{ atm}$$

$$T_0 = 6.00\text{E}+02 \text{ }^\circ\text{K}$$

$$\lambda = 10.6 \text{ } \mu\text{m}$$

$$\rho_0 = 2.00\text{E}-03 \text{ g/cm}^3$$

$$D = 8.00\text{E}+05 \text{ cm/s}$$

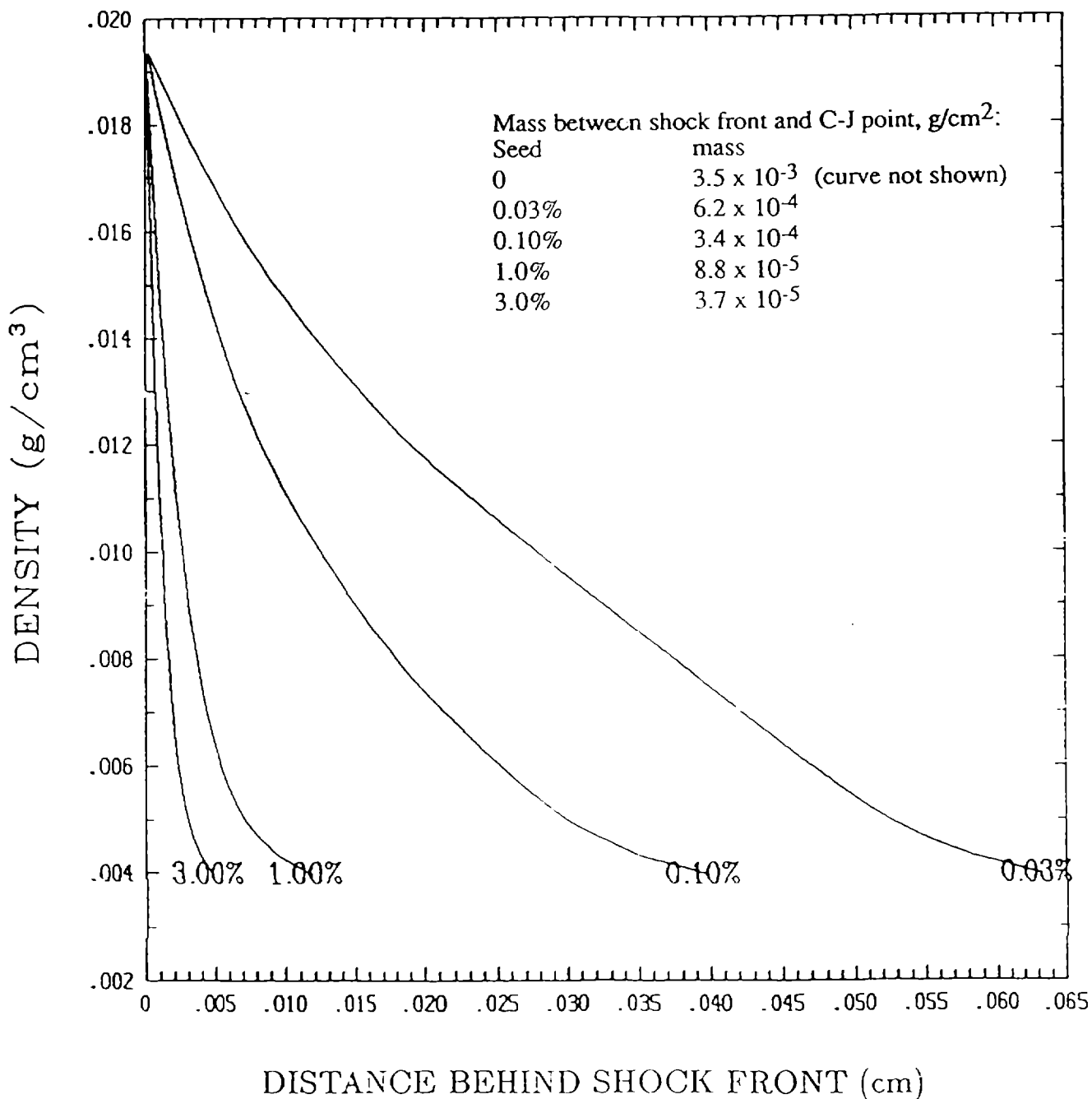


Figure 11: Effect of Li Seed on LSD Wave in Water Vapor
(PSI 1-D steady state calculation)

C. Temperature

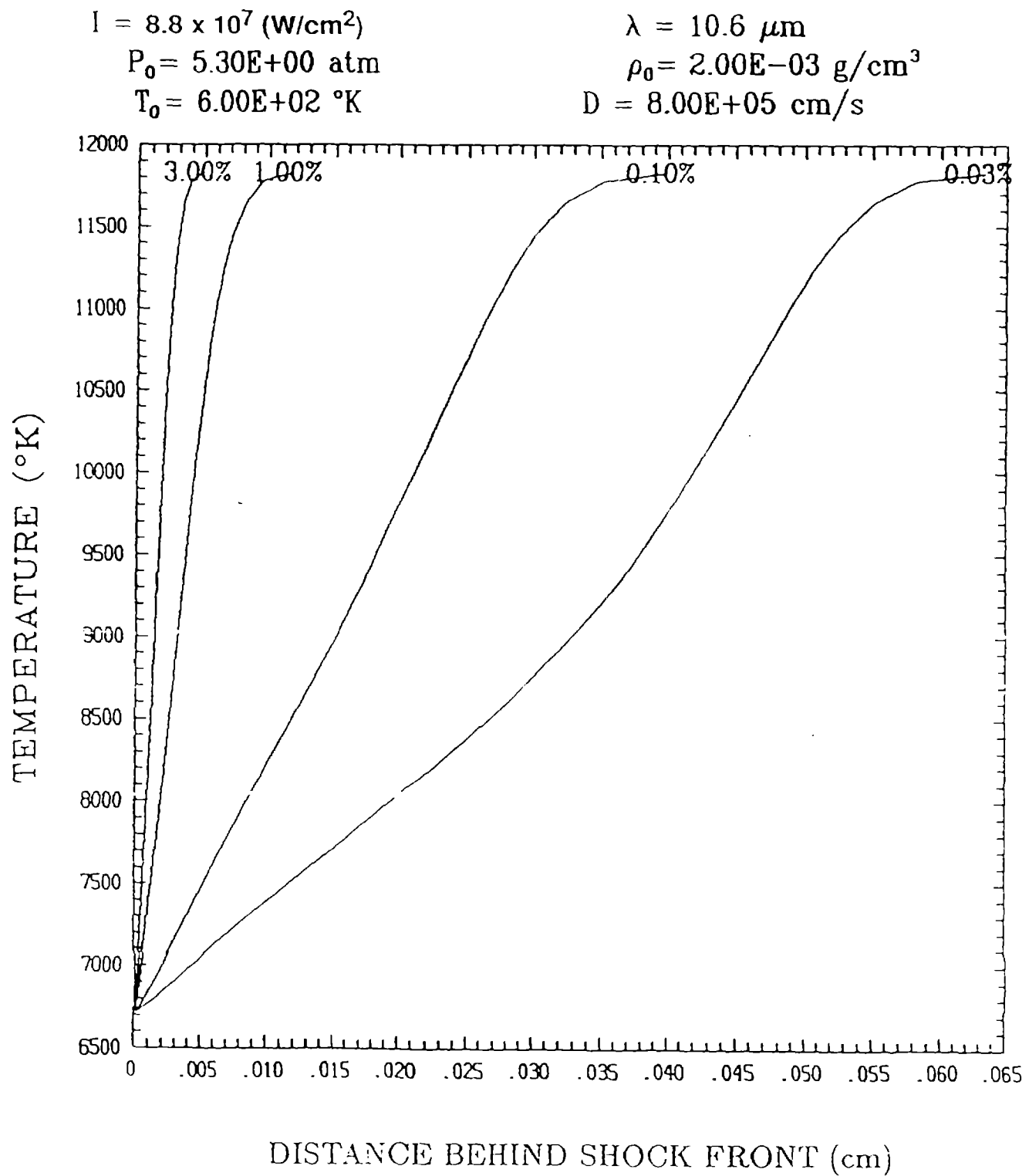


Figure 11: Effect of Li Seed on LSD Wave in Water Vapor
(PSI 1-D steady state calculation)

D. Absorption Coefficient

$$I = 8.8 \times 10^7 \text{ (W/cm}^2\text{)}$$

$$P_0 = 5.30\text{E}+00 \text{ atm}$$

$$T_0 = 6.00\text{E}+02 \text{ }^\circ\text{K}$$

$$\lambda = 10.6 \text{ } \mu\text{m}$$

$$\rho_0 = 2.00\text{E}-03 \text{ g/cm}^3$$

$$D = 8.00\text{E}+05 \text{ cm/s}$$

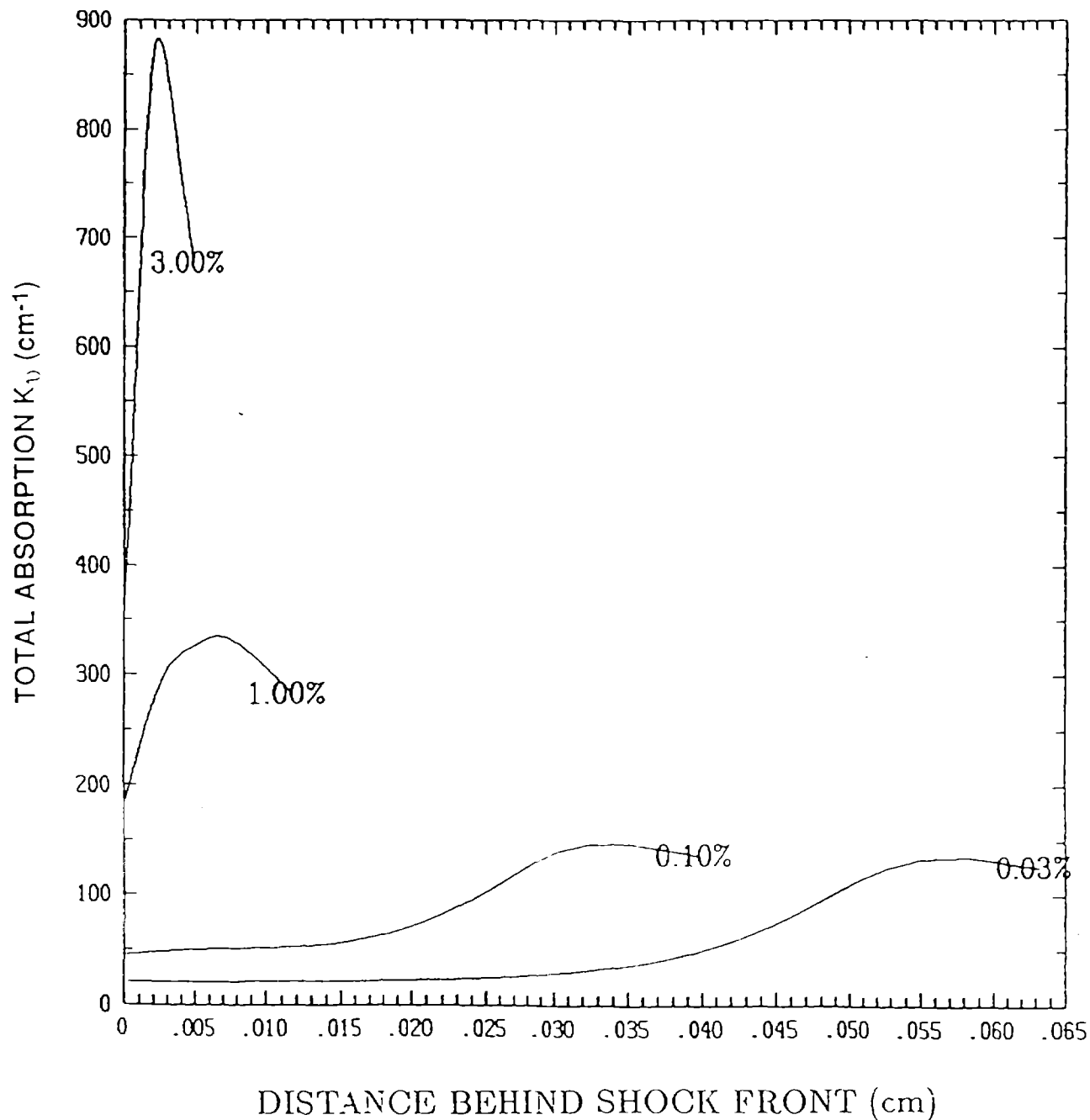


Figure 12: LSD Wave in Lithium Hydride
(PSI 1-D steady-state calculation)

$$I = 5.1 \times 10^6 \text{ (W/cm}^2\text{)}$$

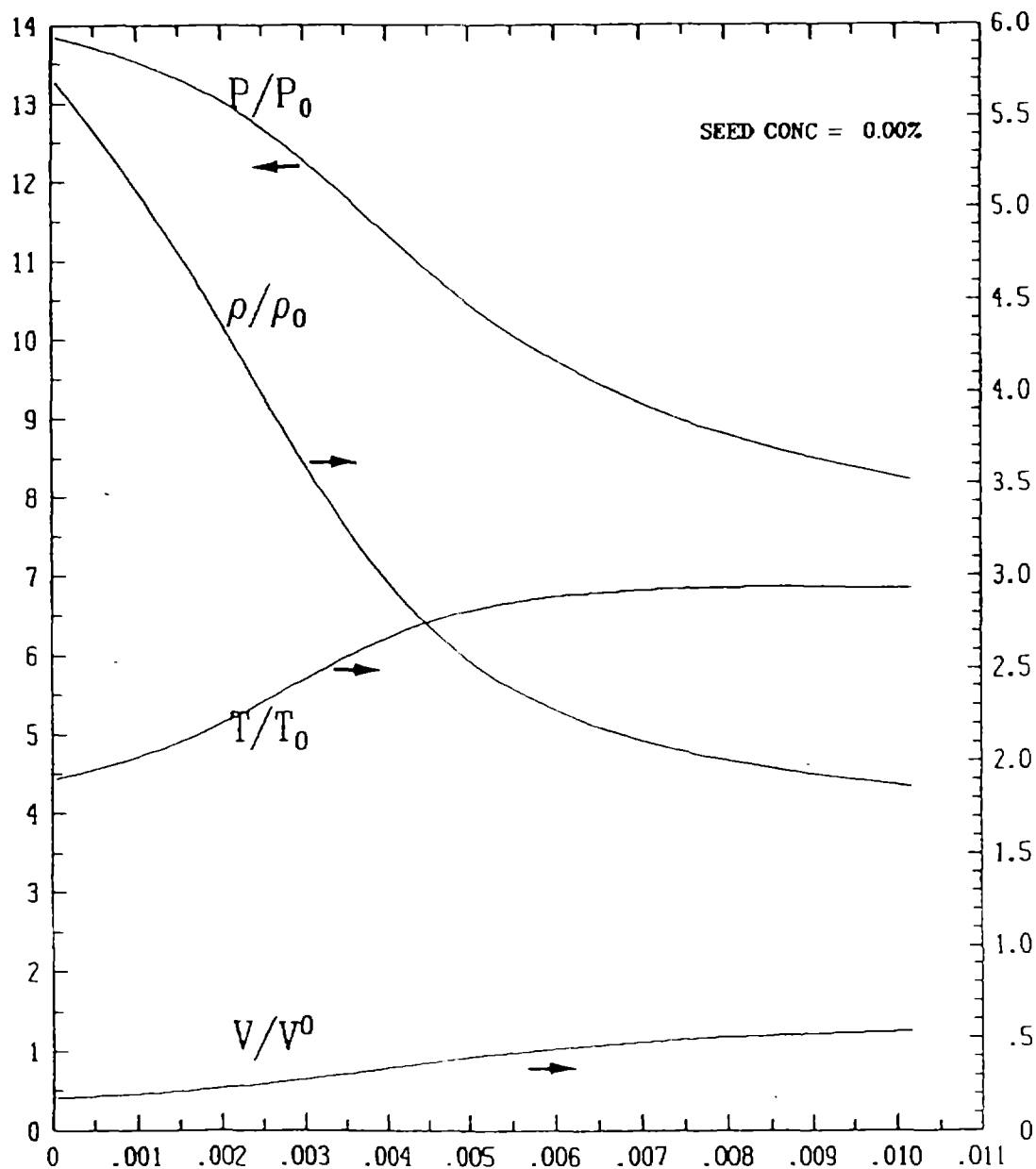
$$P_0 = 4.60\text{E}+00 \text{ atm}$$

$$T_0 = 3.00\text{E}+03 \text{ }^\circ\text{K}$$

$$\lambda = 10.6 \text{ } \mu\text{m}$$

$$\rho_0 = 1.00\text{E}-04 \text{ g/cm}^3$$

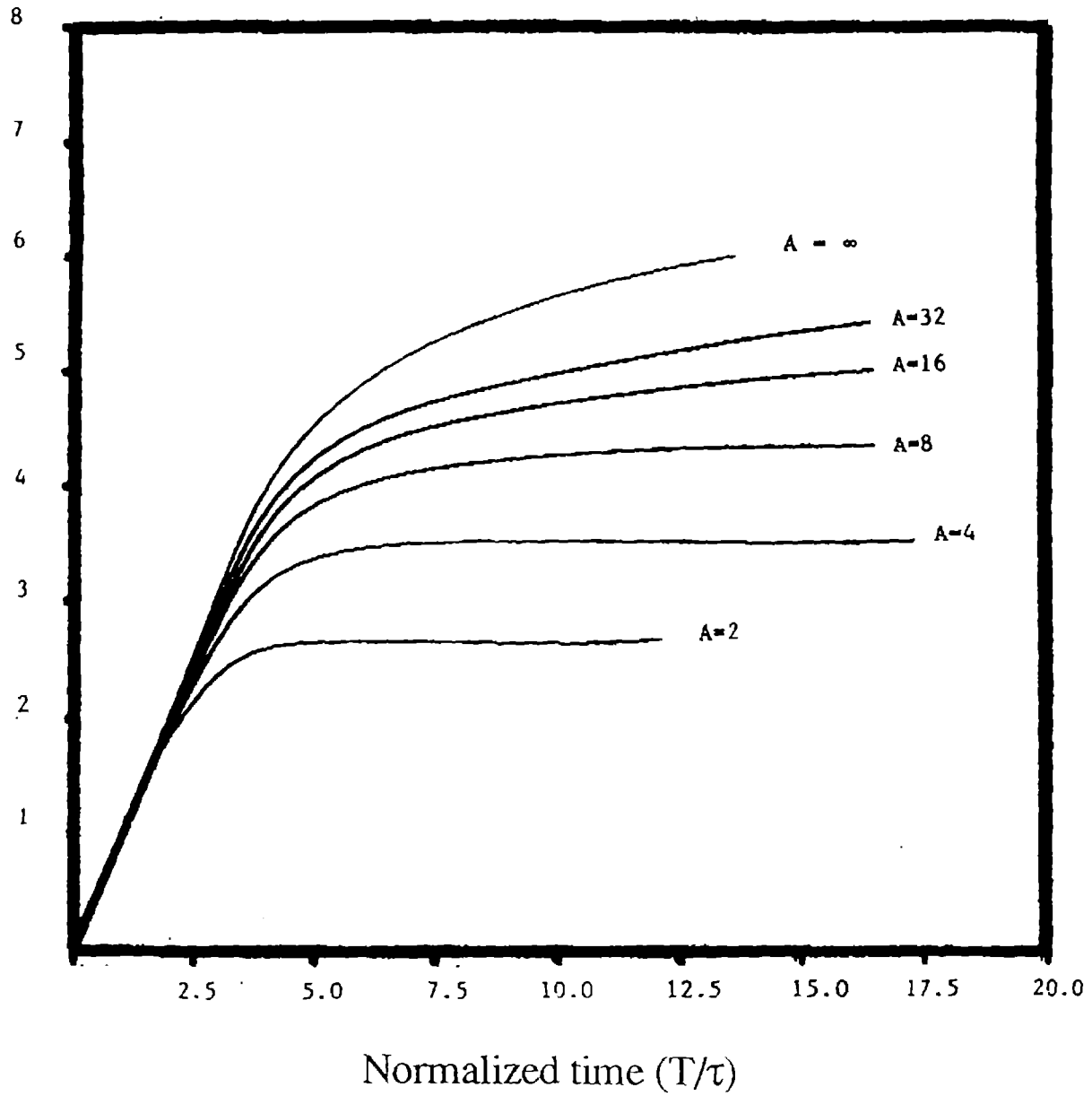
$$D = 8.53\text{E}+05 \text{ cm/s}$$



DISTANCE BEHIND SHOCK FRONT (cm)

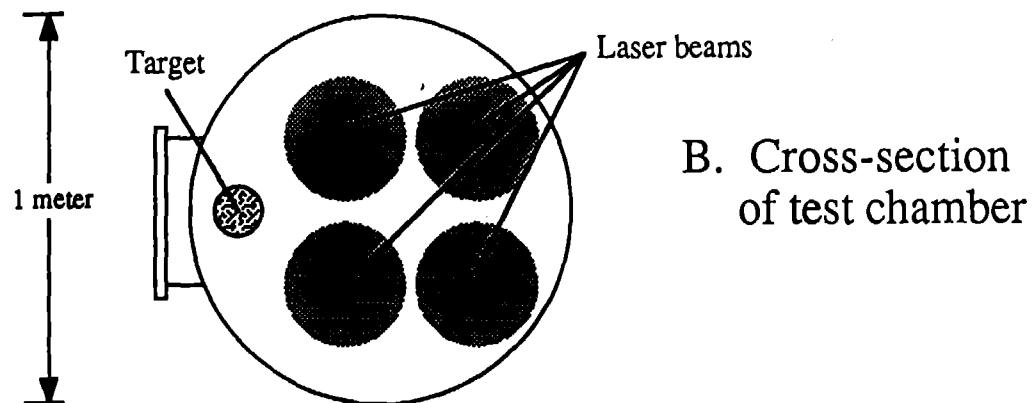
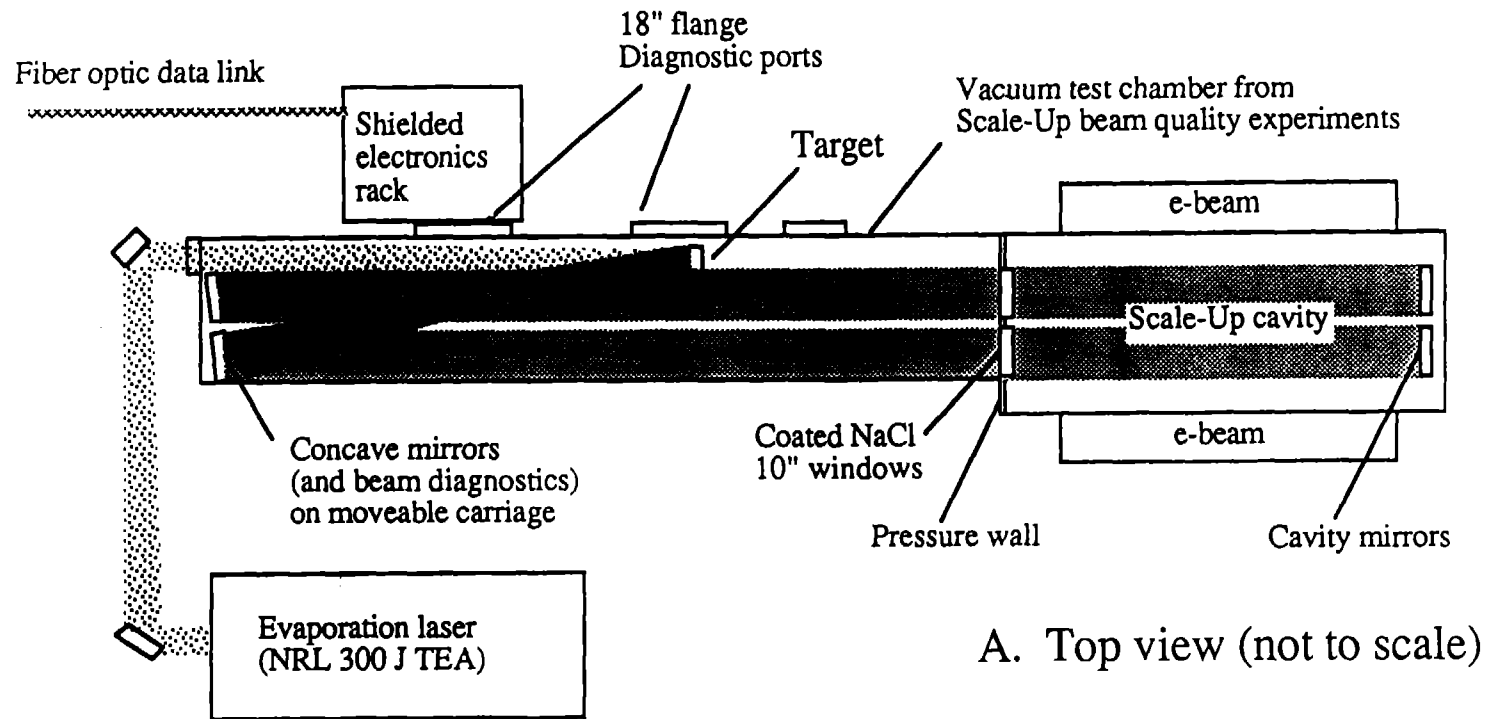
Figure 13: Effect of Thruster Diameter on Total Impulse

Normalized total impulse



Stanford University 2-D calculations of total impulse for various "aspect ratios" A . The aspect ratio is the ratio of the diameter of the thruster to the LSD-wave propagation distance $D\tau$. D is the LSD wave propagation velocity, τ the laser pulse duration. The initial conditions assume a uniform-density slug of perfect gas ($\gamma = 1.2$) of thickness $D\tau$ heated to a uniform temperature; the laser absorption process itself is not modelled. The gas slug expands into a low but nonzero background gas density.

Figure 14: Scale-Up CO₂ Experiment Layout

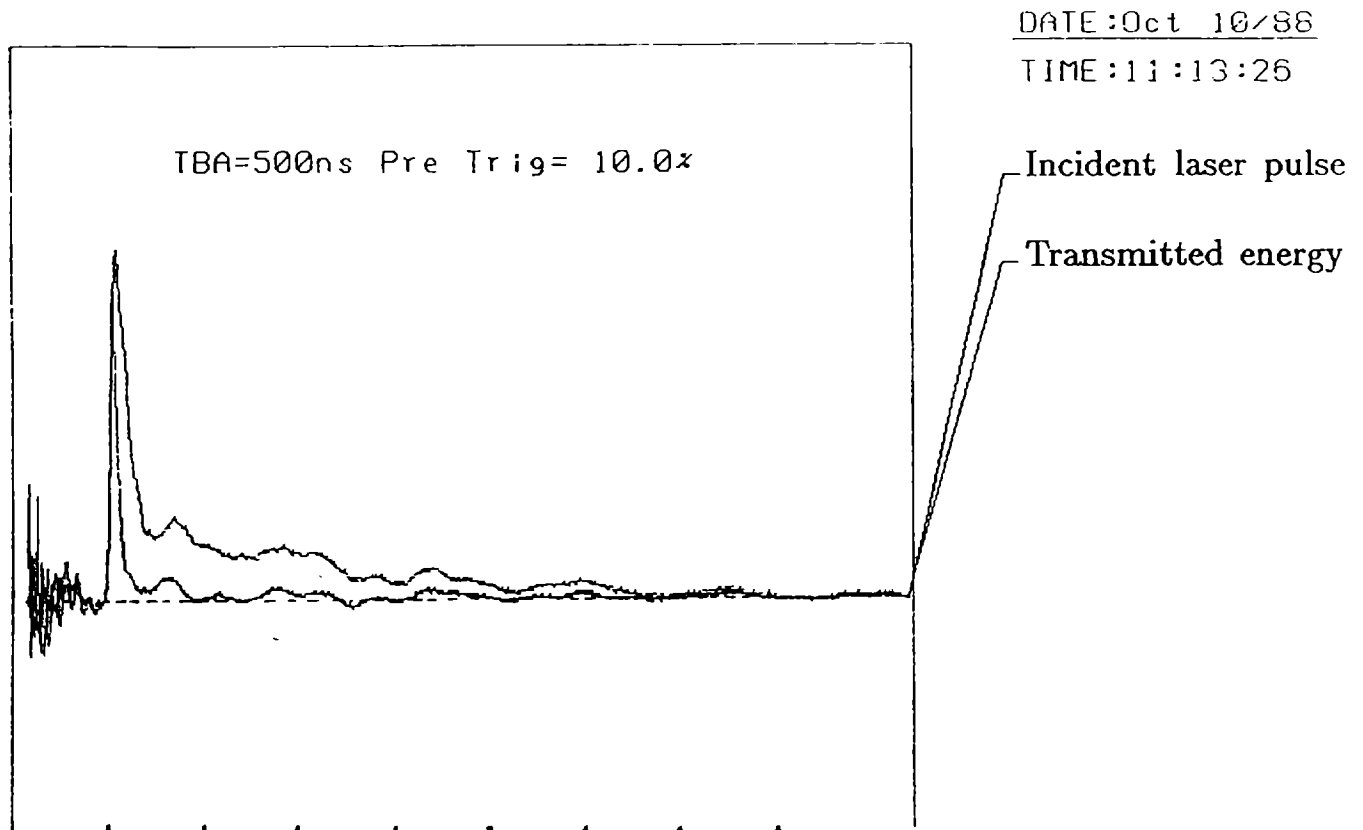




Air-Breathing Laser Propulsion: Breakdown on a Dimpled Plate

CO₂ TEA laser pulse produces a regular array of breakdowns 3 mm above the surface of a copper plate; machined 7mm diameter "dimples" focus the incident flux of 10^7 w/cm² to greater than 10^9 w/cm². Small-scale tests have already demonstrated coupling coefficients on dimpled plates of 20 dyne-s/joule – enough to lift 50 lbs. with a 1 MW laser

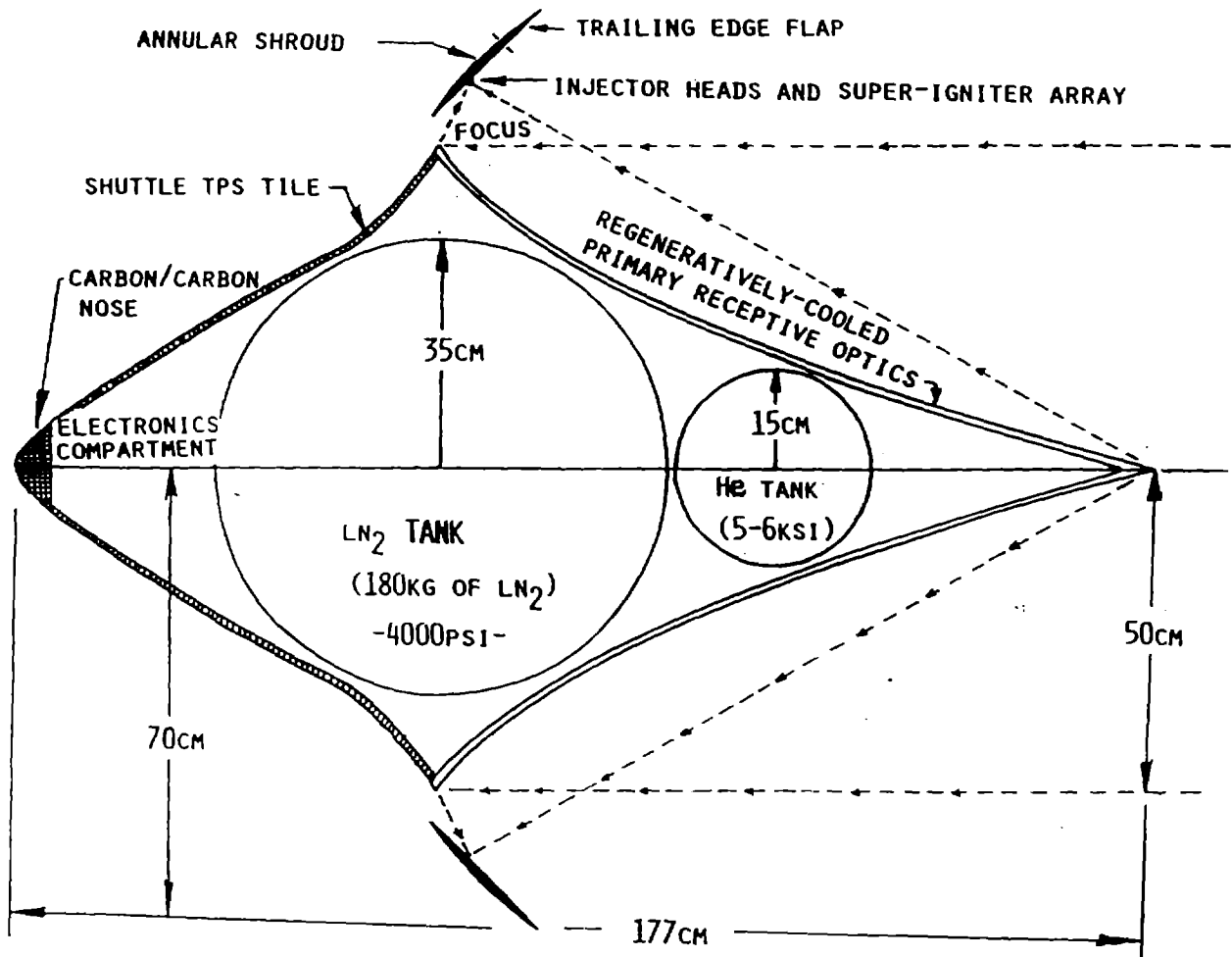
Figure 16: Pinhole Transmission Measurement on
Dimpled Reflector



Measurement of 5 J/cm^2 laser pulse incident on 7 mm diameter f/1 dimples machined in copper plate. Energy is transmitted through a 0.5 mm diameter pinhole in center of one dimple. Full trace is $5 \mu\text{s}$ wide; the incident pulse spike fwhm is approx. 100 ns. The peak incident flux is approx. $1.7 \times 10^7 \text{ w/cm}^2$; the breakdown flux is approx. $1.5 \times 10^7 \text{ w/cm}^2$.

Measurements made with pyroelectric detectors with 2 ns rise time; traces scaled to overlap leading edges (i.e., actual flux levels are not calibrated). Plate is at a small angle (10 degrees) to laser beam, so part of the breakdown delay may be associated with the expansion time of the plasma after breakdown.

Figure 17: Lightcraft Technology Demonstrator



A combined supersonic air-breathing and rocket mode laser driven vehicle. The liquid nitrogen propellant also serves as reflector coolant and as cold-gas propellant for attitude control on orbit. The conical afterbody serves as a laser reflector, a plug nozzle, and, on orbit, as the collecting optic for reconnaissance or other sensors. Designed by Prof. Leik Myrabo, RPI.